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Intensive worldwide deployment of nuclear power could prove necessary to mitigate global warming and fossil fuel shortages while still satisfying a growing demand for energy. We present scenarios for such deployment and bring to light the constraints, such as the availability of fissile matter and the build up of Plutonium stockpiles according to the reactor types considered. Pending the availability of reactors able to breed their fuel, a fleet of 2nd ant 3rd generation light water reactors will have to be built. These can ensure a growth of nuclear power for the coming 20 to 25 years and the transition to sustainable 4th generation nuclear reactors. We show that at least one comprehensive and balanced solution can be found, which reconciles fuel cycle closing, non-depletion of natural resources, reduced long lived waste production, and the option to stop or restart nuclear power rapidly.
It rests on the combination of light water reactors and converter reactors needed to incinerate Plutonium and produce Uranium-233, leading to a reactor fleet widely based on the Thorium-Uranium-233 fuel cycle. The flexibility of this solution and its naturally reduced long lived waste production makes it appear optimal in view of sustainable, intensive nuclear power generation.

Introduction

The worldwide demand for primary energy is increasing and, if the demand is to be met, solutions have to be put together and the degree to which these solutions are adapted to the stakes have to be examined. Not so many options are available if recourse to fossil fuels is to be limited as much as possible to curtail greenhouse gas emissions.

Fission nuclear energy is, along with new renewable energies and, in the longer term, fusion nuclear energy, one of the primary energy sources liable to respond significantly to the demand. Yet the conditions for such a response have to be examined and, in particular: with which reactor types? With which fissile matter? With what long lived waste production?

The aim of the present study is to examine the possibilities and limitations for a worldwide deployment of nuclear power. In this view, we have, in particular, concentrated our attention on verifying the amounts of Uranium 235 available as this is the only natural fissile element and, as a consequence, a major constraint in the frame of sustainable development[1]. In a second step, we have turned our attention to the possibility of eventually stopping the various reactor fleets that would have been started, taking in consideration only the heavy nuclei whose management is tricky.

We first established a frame within which our deployment scenarios would take place: the time frame, the production objectives over that time, and the levels of natural Uranium and Thorium resources.

Worldwide Energy Demand Projection and Share of Nuclear Power

We have chosen a relatively long time span in order to be able to verify that the scenarios considered are sustainable and also to be able to include reactor types that are still in the development stage and will reach industrial maturity in the next 20 years or more. As a consequence, our projections for energy demand extend to 2050. They are further extended in a rather conservative manner until 2100 to allow for better evaluation of the sustainability of the solutions considered.

As an aid to making our projection, we have broken up the annual energy demand into three terms whose individual variation can be approached with some verisimilitude:

$$E = E/GNP * GNP /N * N$$

with:

N: the world population; according to some widely accepted demographic studies, the population should grow from 6 billion today to 9 billion in 2050. This yields a factor 3/2 in our formula.

GNP/N: the per capita gross national product; depending on the references, annual per capita GNP growth lies between 1.5% and 3%. For 2050, then, this gives us a factor between 2.1 and 4.4.

E/GNP: the energy intensity; this includes technological breakthroughs and energy savings. We set this term to 0.5, a voluntarily optimistic and constraining value.

The worldwide energy demand in 2050 would thus be 1.6 to 3.3 times greater than that of today. In our study, we picked a low value within this interval, setting the multiplication factor to 2.

Year	2000	2050
Primary Energy (Gtoe) :		
Fossil fuels (oil + gas + coal)	8	8
Renewables (Hydroelectric + solar + wind +…)	0.7	5.3
Nuclear (fission)	0.6	5.3
Total	9.3	18.6

Table 1: Worldwide demand for commercial primary energy (2000: observed values, 2050: our projection).

As for the contribution of each primary energy source, if the fossil fuels are kept at their current level – which is too high in view of the global warming issue and yet will be difficult to achieve – and if the remainder is shared equally between renewable energies and nuclear power, the resulting values are shown in Table 1, in which only “market” energies are considered, excluding traditional wood energy which represents 1 Gtoe today.

1970	2000	2015	2050	2100
0 TWhe	2400 TWhe	2800 TWhe	18000 TWhe	32400 TWhe
0 GWe.yr	340 GWe.yr	400 GWe.yr	2570 GWe.yr	4630 GWe.yr

Table 2: Projection of the annual nuclear power produced after 2000, expressed in terawatt.hours of electric power (TWhe) and in electric GigaWatt.years (GWe.yr) with a reactor operating ratio at 80%. The values up to and including 2000 are observed values.

How should nuclear power progress from 0.6 to 5.3 Gtoe, at what speed? Here again, we have made hypotheses which we summarize in Table 2. As shown, we assume quasi constant production between 2000 and 2015, then an annual 6.2 % power increase up to 2050, reaching an annual production of 2570 GWe.yr (GigaWatt.year of electricity). We extend the study until 2100 with a slow progression of 1.1 % per year, in order to verify to what degree the scenarios we evaluated are sustainable. Our purpose with these numbers is to obtain orders of magnitude which allow us to test to what degree nuclear power can meet the targeted production. This scenario is very optimistic as to energy savings and the contribution of renewable energies and yet, it does not reduce greenhouse gas emissions since the contribution of fossil fuels is merely stabilized. It is thus probably a minimal scenario for nuclear power.

Natural Uranium and Thorium Reserves

Reserves are the fraction of a resource that can be extracted at a given cost. Regarding natural Uranium, 2 million metric tons (2 MtU) have already been extracted; the extraction cost today is \$30/kgU. The established reserves amount to 1.6 MtU for an extraction cost of \$40/kgU and 2.6 MtU for an extraction cost of \$80/kgU. 2.6 MtU cover only 40 years of consumption at the current level. With an extrapolation up to an extraction cost of \$400/kgU, these “conventional” reserves can be estimated to amount to 23 MtU. It is this deliberately optimistic value that we have retained in our scenarios, although most studies [2] retain 8 to 17 MtU.

Like Uranium-238, Thorium-232 is a fertile element. Just as Uranium-238 can be converted to Plutonium-239 which is fissile, Thorium-232 can be converted to Uranium-233 which is fissile. Thorium is abundant, three to four times as much so as Uranium. In our scenarios, we set the Thorium reserves to the same amount as those of Uranium for easier comparison between the two resources, all the more so since only small amounts of fertile matter are consumed in the reactors. Natural Uranium reserves are a critical issue where the consumption of fissile matter is concerned, i.e. the consumption of Uranium-235.

Reactor Types

We have considered three main reactor types:

- Light water reactors of the second (current Pressurized Water Reactor) and third (EPR) generation. These are not breeder, not even iso-breeder, reactors. PWRs are currently operational, EPRs start in 2010 in our scenarios.
- Fast Neutron liquid metal cooled Reactors (FNR). These are fourth generation reactors, based on the ^{238}U-Pu fuel cycle. Their breeding ratio depends on the scenario considered. FNRs start in 2025 in our study.
- Molten Salt Reactors (MSR) [3,4,5]. These are fourth generation reactors, based on the Th-^{233}U fuel cycle and a thermal neutron spectrum. They start as iso-breeders in our scenarios and could eventually achieve a larger breeding ratio. MRSs start in 2030 in our study.

Scenario with Light Water Reactors Only

With PWR type reactors and, starting in 2010, EPRs, the solution that is most favourable to nuclear power deployment implies “optimized” management of fissile matter. This consists, first, in resorting to the multi-recycling of Plutonium in the EPRs [6], these being, in principle, capable of such multi-recycling. It consists also in thrifty handling of the ^{235}U. In this scenario, two steps are taken in this view: first, the depleted Uranium that is rejected after the enriching process contains 0.1 % instead of 0.3 % of ^{235}U today. Secondly, since the Uranium in the spent fuel still contains 1 % ^{235}U, it is re-enriched instead of being considered as waste, as it is today. Even with this optimized management of fissile matter, however, the ^{235}U reserves are depleted by 2085 as shown on figure 1 (black curve). In fact, the natural fissile Uranium that is still available is already allocated as fuel for the running reactors and it becomes impossible to start the new reactors that would be needed to follow the target demand curve.

This solution is obviously non-sustainable, with the additional drawback that it renders any subsequent recourse to nuclear power impossible once the resource is fully depleted. Indeed, the remaining Plutonium would be degraded and hardly fit for use in a reactor: the multi-recycled Plutonium would contain too many neutron capturing nuclei that do not fission easily. Moreover, Plutonium multi-recycling, which is complex and expensive, would result in the production of large amounts of minor actinides whose management would be problematic.

Scenario with Light Water Reactors and Fast Neutron Reactors

In this scenario, Plutonium multi-recycling in the EPRs is excluded since the Plutonium produced in the pressurized water reactors is needed as fuel for the FNRs. Thus, the fuel for the light water reactors is enriched Uranium and the fuel for the FNRs is based on Plutonium and depleted Uranium. The FNRs are assumed to be Plutonium breeders. A light water reactor (PWR or EPR) produces, in its life span, the Plutonium needed to start one FNR. From 2025 on, the strategy in the scenario is to start an FNR preferably to an EPR. Thus, if the Plutonium needed to fuel an FNR during its entire life span is available, an FNR is started. Otherwise, an EPR is started. With this scenario, the target demand curve can be followed. The fleet of light water reactors is multiplied by 5 as compared to those running today, in order to produce the Plutonium that is needed to start the FNRs, which become predominant in 2080. Since they are breeder reactors, it is no longer necessary to produce Plutonium in the EPRs which can taper out. The pressure on the natural Uranium resource is much less intense than in the preceding scenario: 35% of the reserves are still available when the EPRs are stopped.

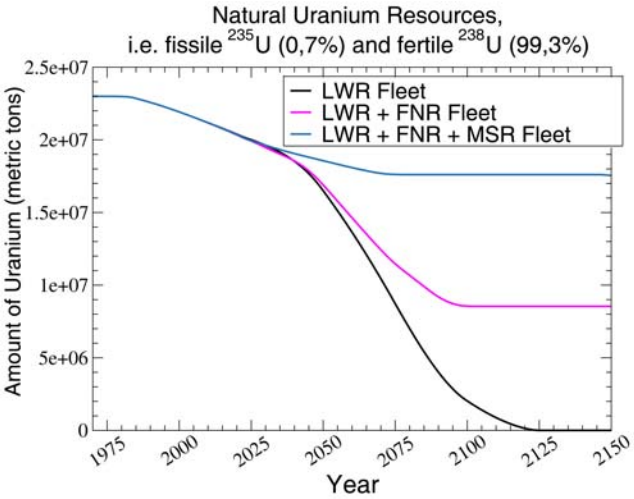

Figure 1: Natural Uranium resources versus time in the three scenarios considered.

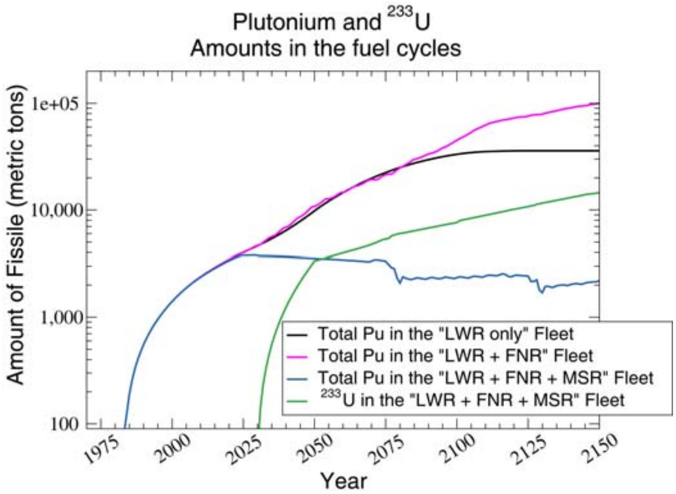

Figure 2: Plutonium and ^{233}U amounts in the reactor fuel cycles versus time in the three scenarios considered.

This scenario has drawbacks, however, that prevent it from being considered sustainable. First, it would not be able to satisfy a larger energy demand; secondly, as shown in Figure 2 (magenta curve), very large amounts of Plutonium (60 000 metric tons in 2100) and of minor actinides are accumulated in the reactor cores and in the fuel processing plants, requiring complex management of this fissile matter. Moreover, in the event of a decision to forgo recourse to nuclear power, these stocks would have to be incinerated and this would be a long and difficult process. Indeed, a 1 GWe reactor, whether it is modified to operate as a burner or not, consumes approximately 1 ton of fissile matter (Plutonium in this case) per year, at most.

The strategy in this scenario is to start, from 2025 on, an FNR provided enough Plutonium is available, so as to favour the consumption of Plutonium stocks. From 2030 on, if an FNR cannot be started for lack of Plutonium, but enough ^{233}U is available to start an MSR, an MSR is started. Otherwise, an EPR is started. The role of the FNRs, here, is to produce ^{233}U and to reduce the stocks of Plutonium, thus closing the U-Pu fuel cycle.

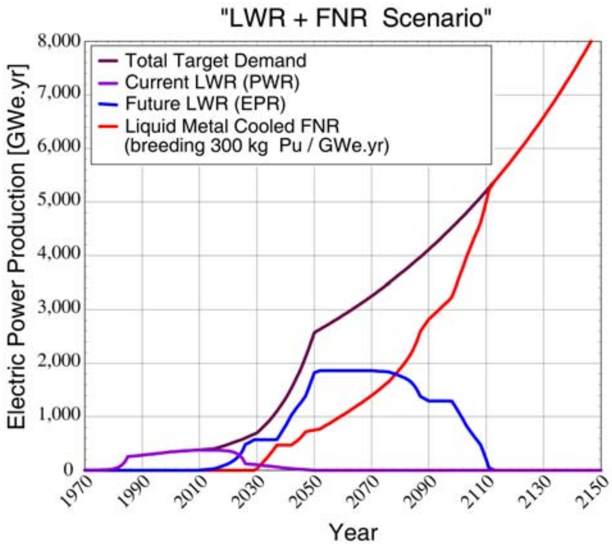

Figure 3: Deployment of the nuclear power fleet with light water reactors and fast neutron reactors.

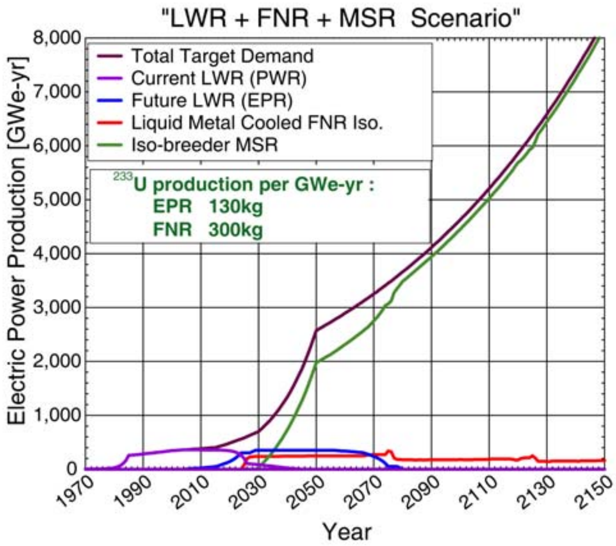

Figure 4: Deployment of the nuclear power fleet with light water reactors, FNRs and MSRs.

As shown in Figure 4, the MSRs become predominant in 2040. The transition towards generation IV reactors is completed in 2080 or so, when the last EPRs are stopped. With this scenario, the target demand curve is followed without difficulty. The amounts of Plutonium (Figure 2, blue curve) and minor actinides produced are much smaller than in the preceding scenario. Only one third of the ^{235}U natural reserves (see Figure 1, blue curve) and a small fraction of the Thorium reserves are consumed. Moreover, since the MSRs operate with 5 to 6 times less fissile matter than the FNRs (see Figure 2, magenta and green curves), if need be, nuclear power could be stopped within a reasonable time period and without accumulating large stockpiles of fissile matter. It would later still be possible to resort again to nuclear power since the ^{235}U reserves are not depleted. Finally, the Thorium fuel cycle option gives rise to a much smaller waste production.

Conclusion

These studies show that intensive deployment of nuclear power is possible but that it requires careful management of fissile matter resources and of wastes. The scenario that combines the three reactor types is by far the most favourable to the flexible deployment of nuclear power, it could meet a more intensive energy production requirement than the one projected in this study, if this were to prove necessary. The three reactor types complement each other remarkably; the consumption of natural fissile matter is optimized, the volume of wastes is minimized, the possibility to stop, then restart nuclear power production is ensured, so that decisions are not irreversible. Intermediate scenarios, emphasizing more or less the role of FNRs versus MSRs could be considered, to satisfy regional or other criteria but it appears, in view of these studies, that it will be necessary to resort to the ^{233}U-Th fuel cycle very soon.

Methods

Our programming environment called DALI is a toolbox in C-language. These tools are clustered in modules characterized by their own functionalities. A detailed description of this environment is given in reference [7].

For these scenario evaluations, we developed a specific module, called Scenarios for the Future, to simulate the evolution of a fleet of nuclear power generators, given a number of constraints, in particular the worldwide energy demand projection and the limits on the fissile matter resources available. We have designed a parameterised calculation algorithm based on the definition of the fleet of reactors considered, on the precise characterisation of the reactors themselves (lifetime, fuel, waste production…) and of the materials necessary (natural resources, stockpile…), together with the objectives of the scenario in terms of energy production for the full deployment period.

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References

1. The Future of Nuclear Power, An Interdisciplinary MIT Study, http://web.mit.edu/nuclearpower, Massachusetts Institute of Technology, Chapter 4 (2003)

2. Uranium 2001: Resources, Production and Demand, *OECD Publishing / International Atomic Energy Agency (IAEA)* (2002)

3. L. Mathieu, D. Heuer et al, The Thorium Molten Salt Reactor: Moving on from the MSBR, *submitted to Progress in Nuclear Energy* (2005)

4. E. Merle-Lucotte et al, Molten Salt Reactors and Possible Scenarios for Future Nuclear Power Deployment, *Proceedings of the Physor 2004 conference "The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments", American Nuclear Society (Ed.)*, 1-12 (2004)

5. A. Nuttin et al., Potential of Thorium Molten Salt Reactors: Detailed Calculations and Concept Evolution With a View to Large Scale Energy Production, *Progress in Nuclear Energy*, **46**, #1, 77-79 (2005)

6. Youinou G., Varaine F., Vasile A., Plutonium and Americium Multirecycling in the European Pressurized Reactor (EPR) Using Slightly Over-Moderated U-235 Enriched MOX Fuel Assemblies, *presented at the International Conference on Advanced Nuclear Energy and Fuel Cycle Systems (Global 2003),* New Orleans, USA (2003)

7. Heuer D., Management of different data types encountered in the analysis of nuclear physics experiments in the DALI development package, *N.I.M. A*, **324**, 569, (1993)